Pulsed Laser Testing Methodology for Single Event Transients in Linear Devices

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I. Introduction

LINEAR circuits produce single event transients (SETs) when exposed to ionizing particle radiation in space. Before they can be used in spacecraft electronic systems, they must be tested for their SET sensitivity at a heavy-ion accelerator facility, a costly undertaking that frequently involves considerable delays.

Linear circuits may be used in an almost unlimited number of configurations (e.g., supply voltage, input voltage, output impedance and gain.) Previous testing has suggested that characteristics (pulse-shape and cross-section) of SETs in certain linear circuits depend on configuration [1,2,3]. This means that SET test results for a specific configuration do not necessarily apply to a different configuration. Clearly, it is not cost effective to repeatedly test the same device in a large number of different configurations, and any method that reduces the amount of accelerator testing merits consideration. It is our contention that a pulsed picosecond laser can be used to reduce the amount of accelerator testing if judiciously applied.

Numerous reports in the literature describe the application of a pulsed laser to the evaluation of SETs in linear circuits [4,5,6]. These reports demonstrate the excellent agreement between SET pulse shapes generated by laser light and by heavy ions. For two particular linear devices - a voltage comparator (LM111) and an operational amplifier (LM124) – the shapes of all SETs generated by heavy ions in a variety of different configurations could be matched with SETs generated by a pulsed laser. Metal coverage, always an issue for pulsed laser SEE testing has, for the most part, not limited the acquisition of SETs in linear circuits because most transistors are relatively large and free of metal. In those cases where junctions are covered with metal, it is still possible to produce SETs by focusing the light on areas adjacent to the metal and relying on charge diffusion [4]. Using this approach, it was possible to generate the full spectrum of SETs in all linear devices tested to date.

The current maturity of the pulsed laser technique suggests that it can be part of a standard approach for characterizing the SET sensitivity of linear devices. The approach we are proposing uses the pulsed laser to reduce – *but not eliminate* – the amount of heavy-ion testing required to characterize SETs in linear circuits. The approach is based on analyzing plots of amplitude (ΔV) versus width (Δt) for all SETs generated by pulsed laser light and heavy ions [7]. Once a part has been fully characterized with heavy ions for one configuration, the pulsed laser may be used to characterize it for other configurations, thereby reducing the amount of heavy-ion testing.

II. Background

A. Previous Work

A test methodology for evaluating SETs in linear circuits has previously been proposed [8]. The authors suggest two alternate approaches, one involving modeling and the other pulsed laser testing. It is our contention that, except in those few cases where validated circuit models with all the SPICE parameters are available, a modeling effort is even more time-consuming and costly than accelerator testing, particularly for COTS devices for which manufacturers rarely divulge proprietary circuit parameters. The real strength of the modeling approach is in helping to understand anomalous behavior.

The authors also propose that SET testing be performed with the device included in the actual system, and only those SETs that propagate through the system need be considered. The problems with this approach are (1) is that devices are identified well before an actual system is built, and it is not practical to wait that long before testing is done, and (2) often the same device is used in many applications within a system or spacecraft and this would require extensive testing.

B. New Approach

The methodology we propose involves using both a pulsed laser and heavy ions to characterize SET sensitivity. Preliminary measurements on two very different device types present strong evidence that most SETs are remarkably unaffected by changes in applied voltages and device configuration. Furthermore, in an actual application, many of the SETs will not propagate, being either too small, too narrow or having too high a LET threshold. Therefore, only a few transistors will produce SETs that contribute to the error rate, and they are the only ones that need to be characterized in detail. A requirement for using this approach is that a full characterization of the linear device with heavy ions must be performed. For each ion LET all the transients should be captured with an oscilloscope by setting the trigger level very close to the DC output level. Next, the complete waveforms should be stored so that subsequent waveform analysis may be performed. Plots of ΔV vs Δt should then be generated for all the SETs associated with a particular ion LET. The final step is to determine whether SETs will propagate through a follow-on circuit by inspecting the ΔV-Δt plot. Should the application be for different bias conditions or a different configuration, it will, in most cases, be unnecessary to perform additional accelerator testing. Instead, the pulsed laser may be used to generate new ΔV-Δt plots needed to perform the assessment.

C. *Analysis Using ΔV-Δt Plots*

Figure 1 shows an example of a ΔV-Δt plot obtained for the LM124 operational amplifier in a particular configuration (voltage follower, V_{dd} = 15V, V_{ss} = -15V and V_{in} = 5 V) [9]. Data collection involved focusing the laser light one transistor at a time and using an oscilloscope to capture all SETs as the laser pulse energy was gradually increased. By repeating this procedure for all SET-sensitive transistors, a complete SET spectrum was obtained. A computer program was used to extract values of ΔV and Δt for each SET. The results were then plotted as shown. By referring to a circuit diagram, the identity of the transistor responsible for each (ΔV,Δt) point may be established.

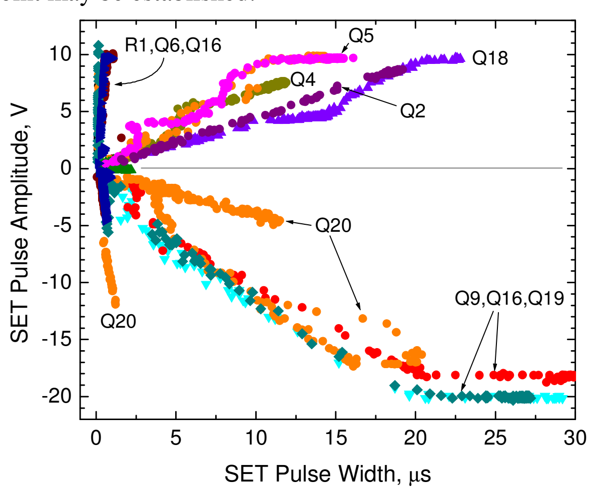

Fig. 1. SET amplitude versus pulse width for SETs generated in the LM124 operational amplifier [9].

SETs induced by heavy ions (LET=59 MeV.cm^2/mg) were also captured and analyzed for the same device under identical operating conditions. Using the same computer program, the values of ΔV and Δt for all SETs were extracted and the resulting data added to the plot with the pulsed laser data. Figure 2 shows such a plot. Clearly, the ion data are coincident with the pulsed-laser data. This result is not unexpected considering the excellent agreement previously observed between individual SET pulse shapes generated by heavy ions and pulsed laser light [4,6]. With this type of plot it is possible to identify the origins of each one of the ion data points, something that is normally not possible when using a broad ion beam. Producing this plot for low LET ions allows one to determine unambiguously which transistors are the most SET sensitive. We note that the data are for a particular configuration, and the question remains as to how the distribution of data points changes with supply voltage, input voltage and device configuration.

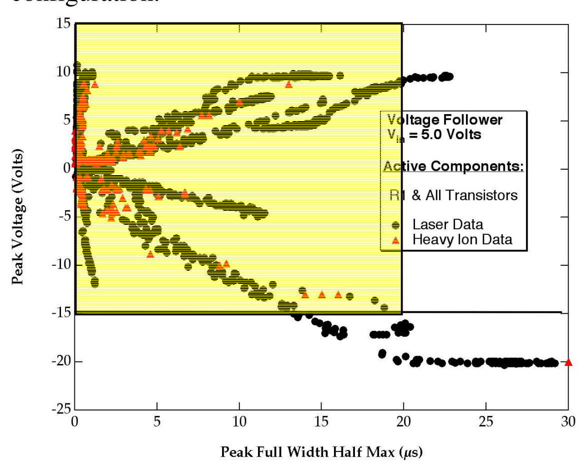

Fig. 2. Plot of ΔV versus Δt illustrating the "phase space" (15V>ΔV>-15V and 15 µs>Δt) where SETs do not propagate. Clearly, the ones that will propagate for this configuration are outside the box and originate in one or more of the following transistors - Q19, Q16 and Q9 [9].

One point previously mentioned is that not all SETs generated in the linear device will propagate through the system as a whole. Some pulses are either too small or too narrow to propagate. Knowledge of the minimum pulse width and amplitude required for SET propagation through a particular system allows for the definition of a region in ΔV-Δt space where SETs can be ignored. This is illustrated in Figure 2 where it is assumed that all SETs with amplitudes smaller than +/- 15 V and pulse widths shorter than 20 µs will not propagate through the follow-on circuitry. The shaded area in Figure 2 delineates the phase space for which propagation through the follow-on circuit will not occur. For this system it is necessary to consider only those SETs that fall outside the yellow box because those are the only ones that will propagate through the system. Those inside the box can safely be ignored.

Figures 1 and 2 together clearly show that transistors Q9, Q16 and Q19 are the only ones capable of producing SETs that meet this requirement. The circuit designer should be able to determine, using circuit simulator programs such as SPICE, the minimum values for SET amplitude (ΔV_{th}) and width (Δt_{th}) for propagation through the follow-on circuits to occur. If the device is to be used in the same configuration but with different follow-on circuitry, the limits of ΔV and Δt on the graph are moved accordingly. The graph is then inspected to ascertain whether there are any SETs that will propagate, i.e., whether any are outside the ΔV-Δt "box".

The ion data in Figure 2 are for ions with the highest LETs used during the run. The pulsed laser is able to deposit more energy than the accelerator ions merely by increasing the pulse intensity. Therefore, it is not surprising that the laser can produce SETs that are larger and longer than those produced by heavy ions. The only limits on pulse amplitude and width are imposed by the circuit response and by thermal damage due to absorption of very high intensities of laser light in the silicon.

III. Test Methodology

Figure 3 shows the steps involved in using a pulsed laser to help qualify a linear part for its SET sensitivity in an ionizing particle environment. Note that the final step always involves an optional accelerator test, except in the case where ion data are already available for the particular configuration being considered. Inspection of all the steps involved suggests that judicious use of a pulsed laser can significantly reduce the amount of heavy ion testing needed to qualify a linear device for SET sensitivity.

The first step in the test methodology is to determine whether any SET data already exist for the configuration of interest. Plots of cross-section as a function of ion LET are necessary but not sufficient. The data should also include complete waveforms for all the captured SETs for each value of ion LET. That data is then used to generate plots of ΔV vs Δt. A computer program has been developed to automatically analyze all the transients and produce plots of ΔV vs Δt, similar to those in Figures 1 and 2. An additional useful feature of the program is the ability to cull from the data plots of ΔV vs Δt for a single transistor under a wide variety of operating conditions. It is then simple to see how the transistor's response depends on operating condition.

To be able to use the methodology, it will be necessary to capture and store all SETs generated during heavy-ion SET testing so that they can be used for analyzing subsequent applications. It will also necessary to consult the design engineer to determine the conditions under which SETs will propagate through the system in order to establish the minimum values of amplitude and width.

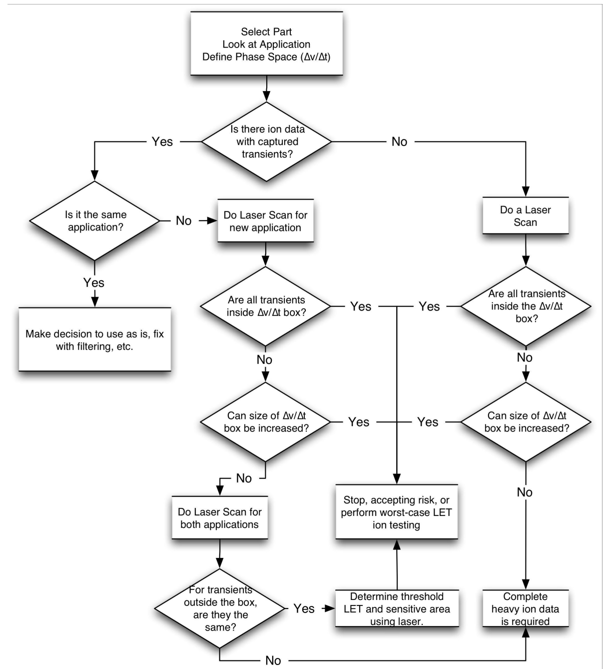

Fig. 3. Steps involved in using a pulsed laser for qualifying a part for SET response.

Two different paths are followed, depending on whether or not SET data are already available. The two paths are discussed in more detail in the following two sections.

A. *No Heavy-Ion SET Data Available*

The situation is relatively straightforward in the absence of SET data. The first step involves a scan in energy of all the transistors on the chip using the laser to determine whether any of the SETs are outside the phase "box" defined by the values of ΔV_{th} and Δt_{th}. (A complete energy scan for each transistor is required because, in some cases, the SETs are actually smaller at higher laser energies – equivalent to higher ion LETs – than at smaller laser pulse energies). If all the points are inside the box, one can either accept the part together with the associated risk that the laser data did not uncover all SETs, or one can perform an ion-beam test using only the highest LET ions available to confirm that all SETs are within the box. If some of the SETs are outside the box, the design engineer should be consulted to see whether ΔV_{th} and/or Δt_{th} can be increased by modifying the follow-on circuit to prevent SET propagation. If the design engineer cannot make the changes, the only option is to perform a complete heavy-ion test.

B. *Heavy-Ion SET Data Available*

There are two possible options for the case where heavy-ion SET data are available. The first is when data are available for the configuration identical to the one of interest. No further ion or laser-beam testing is required and it is a relatively straightforward decision to either accept the data as is because it meets the requirement or, if it does not, to modify the follow-on circuitry, if possible.

The other option – data are available for the identical device but in a different configuration – involves the following steps. The first step is the same as in Section A – a scan in energy of all the transistors using the pulsed laser to determine whether any of the SETs are outside the box. If they are all within the box, one can accept the risk or perform a limited ion test using ions with only the highest available LETs. If some of the SETs are outside the box, the design engineer should be consulted to see whether the propagation requirements on ΔV_{th} and/or Δt_{th} can be relaxed.

If the follow-on circuit cannot be modified to be tolerant of SETs, a scan of all the transistors using the pulsed laser should be done for the original configuration. The laser and ion data for the original configuration are then combined in a single plot, which is compared with the one for the new configuration. If the loci of (ΔV,Δt) points are different for the two configurations, the laser cannot be used and a complete heavy ion test must be done. However, if the same transistors in both configurations are responsible for the (ΔV,Δt) points outside the "box", the pulsed laser can be used to measure LET threshold and cross-section for the new configuration.

The threshold is measured by calibrating the laser energy needed to produce a SET in the new configuration against that in the old configuration. This is done by placing the laser light on the transistor responsible for the (ΔV,Δt) points just outside the box in the old configuration and measuring the energy to produce that point. Then the device is placed in the new configuration and the energy measured at that same transistor to produce a (ΔV, Δt) point just outside the box. Since the ion LET threshold is known for the old configuration, it can be calculated in the new configuration by taking the ratio of the laser energies and multiplying by LET_{th} in the old configuration.

The saturated cross-section is easily measured by using the laser with high pulse energy to determine the sensitive area associated with every transistor that produces SETs outside the "box" no matter what the energy. Summing all those areas gives a saturated SET cross-section that may be larger than the actual saturated cross-section because some SETs decrease in size at higher laser energies or ion LETs.

IV. Examples

Interesting data that shed light on the methodology were obtained from SET testing with pulsed laser light for two different devices – an operational amplifier (LM124) and a voltage comparator (LM111). These results are for only two devices, and therefore limited in scope. Nevertheless, they reveal that, with a few exceptions, most SETs do not vary with applied voltage and device configuration, a quite unexpected result. The clear implication is that, once heavy-ion data have been collected, additional measurements of only a few laser-induced transients need be made to fully characterize the SET response of a device in a variety of different configurations.

A. *LM124*

SETs in the LM124 operational amplifier have been studied in considerable detail for a variety of different configurations. However, no detailed comparisons have been made of SET amplitudes and widths for different configurations.

The first set of data was taken for the LM124 configured as a voltage follower with supply voltage of +/- 15 V and an input of 5 V. The assumption was made that the LM124 would be used in a system for which only negative transients longer than 20 µs would be able to propagate. To measure changes in SET shapes with changes in voltage or configuration, the laser light was focused on a transistor and the resulting SETs were displayed on an oscilloscope. The laser pulsed at a rate of 1 KHz, making it a simple matter to observe in real time any changes in SET shapes. Only transistors Q9, Q16 and Q19 could produce transients 20 µs long. Measurements were made of the energies required to produce those transients. The most sensitive transistor was Q9, which is located at the device output, and the least sensitive was Q16, which is part of the current source. The measured relative amounts of energy required to produce SETs in transistors Q9, Q19 and Q16 were 7:9:12, respectively. Because all the transistors had sensitive junctions at the same depth, the relative laser pulse energies translate directly into relative LETs.

Next, the SETs were carefully monitored while the supply voltages, input voltage and device configuration were changed. A surprising result was that most transients did not change shape with supply voltage (from +/- 10 V to +/- 15 V), input voltage (from 1 V to 5 V) or device configuration (voltage follower to inverting with gain of 11).

There was one parameter, however, that did affect the magnitude, but not the shapes, of the SETs – the voltage range between the output and the rail. As the output voltage increases so does the voltage difference between the output and the negative rail. Larger amplitude SETs are thus possible. Fig. 4 shows the ΔV-Δt for SETs generated at transistor Q19 with pulsed laser light. The data clearly show that the saturated amplitudes (those falling along a horizontal line) increase as the input voltage increases. For example, when the output voltage was set to 5 V, the distance to the negative rail was 20 V and the saturated values are indeed at –20 V. When the output was set to –5.5 V, the SETs had a maximum amplitude of –14.5 V.

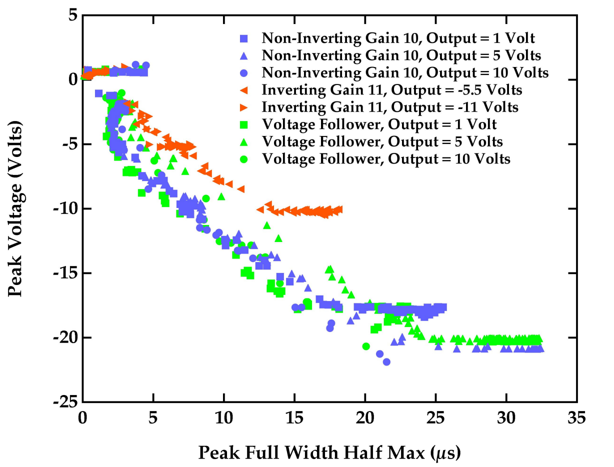

Fig. 4. Plot of SET peak voltage vs width for a variety of input voltages and configurations. Each color corresponds to a different configuration.

Small SETs (amplitude of 1 V) near threshold were also checked for all SET-sensitive transistors. In all cases changes in the supply voltage, input voltage and device configuration had no effect on the transients.

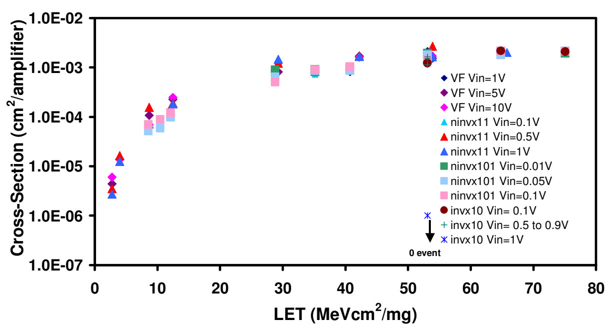

Fig. 5 SET cross-section as a function of ion LET for the LM124 operational amplifier for a variety of different configurations.

Fig. 5 is a plot of SET cross-section as a function of ion LET for a number of different configurations. The plot clearly shows that the LET threshold and saturated cross-section do not depend on device configuration, i.e., all the curves are coincident. These results confirm those previously obtained with the laser and show that, for this device, applied voltages and device configuration play very little role in determining SET rates in space. One set of SETs induced by heavy ions is sufficient to establish a fiduciary base so that SETs in other configurations may be compared quantitatively.

B. LM111

The LM111 was selected for testing because data clearly show that the SET cross-section depends critically on differential input voltage, particularly when the differential input voltage is small. Being a voltage comparator, all SEUs are simple. When the output is at +15 V, all the SETs have negative amplitudes. The pulsed laser was used to scan the chip. Seven transistors and one diode were determined to be SET-sensitive.

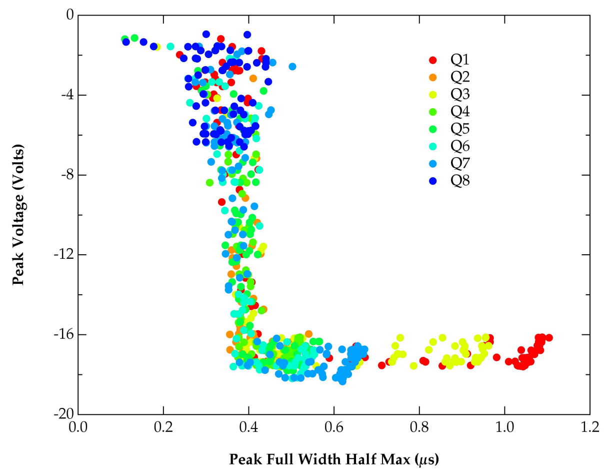

Fig. 5. Plot of SET peak voltage vs width for seven transistors and one diode on the LM111. All the transients have the same shape but different sensitivity. The most sensitive transistor is Q1 and it produces the longest SETs. Vdd = 15V, Vss = -15V, ΔV_{in} = 0.1 V and the resistance of the pullup resistor is 1.7 KΩ.

Fig. 5 is a plot of amplitude versus width for all the SETs observed in the LM111 for a differential input voltage of 0.1 V. The data show that the shapes of all the SETs are identical, no matter their origin. The most sensitive transistors produce the largest SETs with maximum amplitudes of –15 V and maximum widths of just over 1 µs. It is a simple exercise to decide whether SETs generated in the LM111 will propagate through follow-on circuitry if the bandwidth of the follow-on circuitry is known.

The LM111 contains one transistor and one diode whose SET sensitivities depend critically on differential input voltage. As the differential input voltage increases, the sensitivities decrease, and for sufficiently high LETs the transistor and diode are SET insensitive. All the other transistors are not SET-sensitive.

The information obtained with the laser, such as the independence of the SET sensitivities of most of the transistors to configuration and input voltage, can be used to fully characterize the part for any application with a single accelerator run. The only change that occurs with device configuration is the SET sensitivities of the input transistor and diode. Relative measurements of their SET thresholds as a function of ΔV_{in} using a pulsed laser can be used to determine the LET thresholds by multiplying the LET threshold measured with ions by the ratio of the laser pulse energies for the two configurations.

V. Summary and Conclusion

We have proposed a methodology for using pulsed laser light to reduce, but not eliminate, the need for heavy ion testing of linear circuits. The methodology is based on the excellent agreement between SETs obtained from heavy ions and pulsed laser light. The critical requirement is that appropriate heavy-ion data be available with which to compare the pulsed-laser data. By appropriate data is meant that the SET cross-section be measured as a function of ion LET and that every single SET be captured using an oscilloscope and then stored in computer memory for later analysis of pulse amplitude versus pulse width.

If there is no heavy-ion data available and the device is not covered to a large degree by metal, the pulsed laser may be used to determine whether there are any SETs that will be able to propagate through follow-on circuitry.

If there is data available, but the data is for a configuration different from the one of interest, the pulsed laser may be used to ascertain whether SETs will propagate through the follow-on circuits. If the data indicate the presence of sufficiently long or large pulses that will propagate, then the by measuring relative energies for the configuration of interest and the configuration for which data is present, the LET threshold may be calculated. Also, the saturated cross-section may be measured by scanning the transistors with the laser beam and measuring their sensitive areas.

Data was presented for two devices that show that most SETs are independent of applied voltages or configuration. In those linear circuits where there are transistors whose SET sensitivities do depend on configuration or applied voltage, the pulsed laser may be used to measure relative laser pulse energies and that information may then be used to calculate LET.

Finally, if there is doubt regarding the ability of the pulsed laser to produce SETs, such as when a transistor is completely covered with metal, or when different transistors are SET-sensitive in different configurations, the conservative approach should be taken – perform heavy ion testing.

VI. References

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